Programming Assignment #1

RBE 500

Prepared for Prof. Flickinger

By

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11/10/2019

Programming Assignment Details:

Programming Assignment 1: Kinematics

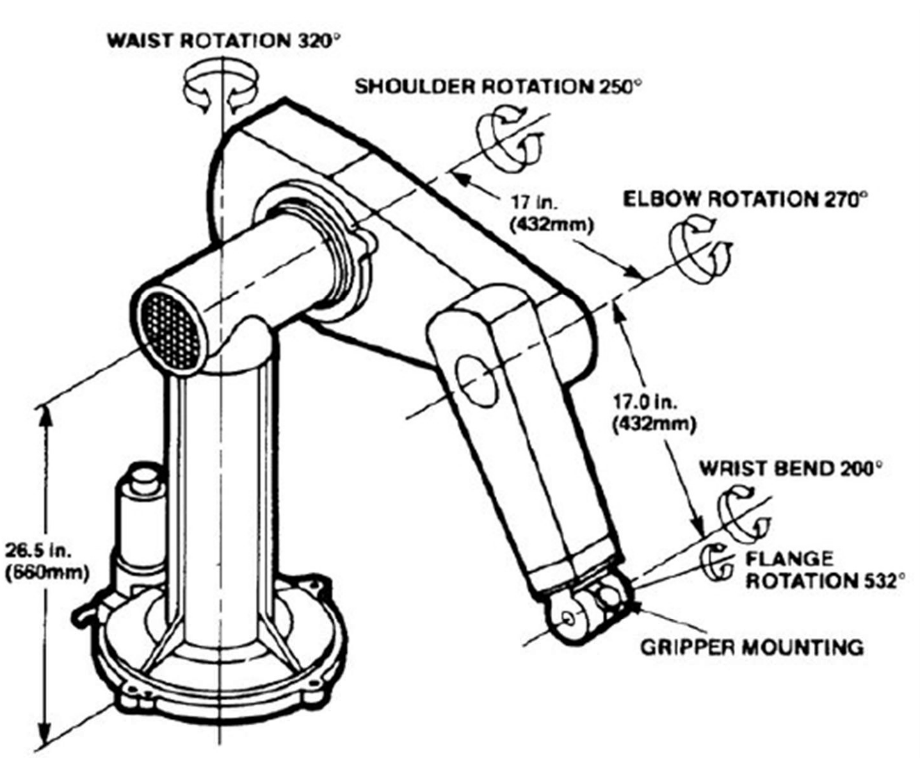
Submit Assignment

Due Thursday by 7am **Points** 100 **Submitting** a file upload
Available Oct 17 at 12am - Nov 21 at 7am about 1 month

Create methods to solve for forward and inverse kinematics for a PUMA 560 robot.

Problem Description

Using MATLAB, Python, Forth, or any other language of your choosing, write a computer program to solve the kinematics of the PUMA 560 robot, as illustrated:



Note that the offset of the forearm link in relation to the waist rotation axis is 149 mm.

Implementation

Implement two high level functions:

- [x,y,z,$\boldsymbol{\varphi}$, $\boldsymbol{\theta}$,$\boldsymbol{\psi}$] = kines_f($\boldsymbol{\theta}_0$, $\boldsymbol{\theta}_1$, $\boldsymbol{\theta}_2$, $\boldsymbol{\theta}_3$, $\boldsymbol{\theta}_4$)
- [$\boldsymbol{\theta}_0$, $\boldsymbol{\theta}_1$, $\boldsymbol{\theta}_2$, $\boldsymbol{\theta}_3$, $\boldsymbol{\theta}_4$] = kines_i(x,y,z,$\boldsymbol{\varphi}$, $\boldsymbol{\theta}$,$\boldsymbol{\psi}$)

which calculate the forward and inverse kinematic solutions respectively, given either joint angles, or an end effector pose. The pose angles are Euler angles.

Reporting

Submit a report with both kinematics methods, all supporting functions, and plots. Demonstrate your forward kinematics solution by producing a table of poses from the following angles:

$\boldsymbol{\theta}_0$	$\boldsymbol{\theta}_1$	$\boldsymbol{\theta}_2$	$\boldsymbol{\theta}_3$	$\boldsymbol{\theta}_4$
45°	-45°	-110°	45°	90°
-60°	20°	-90°	45°	45°
-90°	-90°	-90°	0°	0°
0°	-75°	-120°	90°	35°
-45°	-120°	75°	30°	60°

Note that the zero position of the robot is with the manipulator straight up, along the waist axis.

To demonstrate your inverse kinematics solution, plot all five angles for a parametric path consisting of 50 equidistant points in a line segment between the points [400, 200, 100] mm and [400, 200, 500] mm. Where the world frame Z axis is coincident with the waist rotation axis, and the X axis points to the right of the diagram. The end effector orientation in this example stays fixed aligned with the X axis throughout the entire motion.

Programming Assignment 1 Rubric

Criteria	Ratings					Pts
Forward kinematics implementation Complete and correct implementation of manipulator forward kinematics method.	**20.0 pts** **Correct implementation**	**15.0 pts** **Incorrect implementation** Completed method, but errors in results.	**10.0 pts** **Incomplete implementation** Incomplete, unfinished forward kinematics method.	**0.0 pts** **Not attempted** Forward kinematics not attempted.		20.0 pts
Inverse kinematics implementation Complete and correct implementation of manipulator inverse kinematics method.	**40.0 pts** **Correct Implementation**	**35.0 pts** **Incorrect implementation** Completed method, but errors in results.	**30.0 pts** **Incomplete implementation** Incomplete, unfinished inverse kinematics method. At least you tried.	**0.0 pts** **Not attempted** Forward kinematics not attempted.		40.0 pts
Plots, tables Completed results section, with data tables and plots.	**30.0 pts** **Complete and correct results**	**25.0 pts** **Errors in data** Plots and tables complete, but errors in results.	**15.0 pts** **Incomplete Results** Missing either forward kinematics results table, or inverse kinematics plot.	**0.0 pts** **No Results** Results section completely missing.		30.0 pts
Report Report format, organization.	**10.0 pts** **WITNESS ME**	**8.0 pts** **Minor errors** Minor errors in formatting, but otherwise complete.	**5.0 pts** **Missing sections** Sections missing, organizational issues.	**3.0 pts** **Major errors** Major problems with presentation and completeness.	**0.0 pts** **MEDIOCRE**	10.0 pts
						Total Points: 100.0

Overview:

The tasks given for the programming assignment #1 are to use a programming language and to solve for the forward and inverse kinematics of the PUMA 560 manipulator. The PUMA 560 manipulator given in the assignment description is a 5DOF (Degrees of Freedom) manipulator. The initial three revolute joints are similar to the elbow manipulator. The last two revolute joints are part of spherical wrist. The standard spherical wrist has 3DOF. However, the spherical wrist presented to us has only 2 DOF.

For the forward kinematic equations, the Denavit-Hartenberg (DH) Convention was used to come up with the ai (link length), di (link offset), alphai (link twist), and thetai (joint variables) parameters. The assigned frames as well as the DH table are given in the pages to follow. I wanted to design a PUMA 560 application that would take inputs from a user and output either forward or the inverse kinematic calculation results.

The app designer from Matlab R2019b was used for this program. The program would calculate the forward or inverse kinematic parameters and tabulate them if requested by the user.

For the inverse kinematics portion, an analytical approach was used in coming up with the joint variable equations.

Each of the joint angles given per the assignment has rotational constraints which are taken into consideration in this program.

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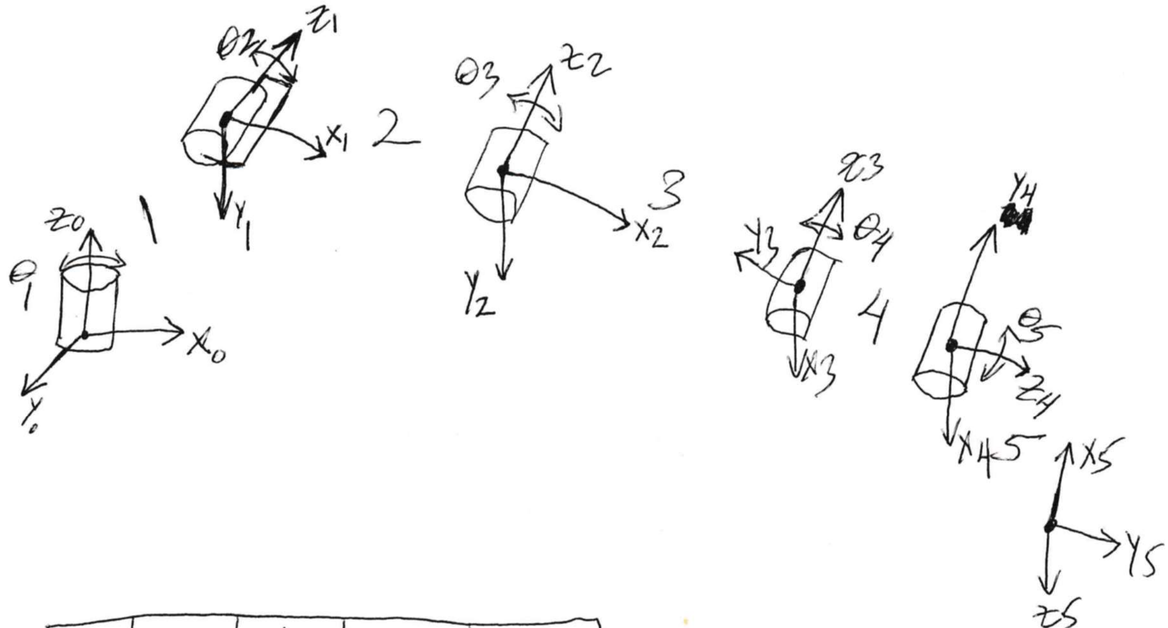
11/10/2019



Link	a_i (mm)	d_i (mm)	α_i	θ_i
1	ϕ	ϕ	$-90°$	θ_1
2	432	-149	ϕ	θ_2
3	432	ϕ	$-90°$	θ_3
4	ϕ	ϕ	$90°$	θ_4
5	ϕ	ϕ	ϕ	θ_5

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$$T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^0 = T_1^0 \, T_2^1 \, T_3^2 \, T_4^3 \, T_5^4$$

identity matrix

$$\rightarrow {T_1^0}^{-1} T_5^0 = (I) \, T_2^1 \, T_3^2 \, T_4^3 \, T_5^4$$

$$\rightarrow {T_3^0}^{-1} T_5^0 = \left({T_3^0}^{-1}\right)\left(T_1^0 \, T_2^1 \, T_3^2\right) T_4^3 \, T_5^4$$

$$\left[T_1^0\right]^{-1}\begin{bmatrix} r_{11} & r_{21} & r_{31} & p_x \\ r_{21} & r_{22} & r_{32} & p_y \\ r_{31} & r_{23} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_5^1$$

$$\begin{bmatrix} c_0 & s_0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ -s_0 & c_0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} r_{11} & r_{21} & r_{31} & p_x \\ r_{21} & r_{22} & r_{32} & p_y \\ r_{31} & r_{23} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} & R & & \sim 1 \sim \\ & & & \sim 1 \sim \\ & & & -149 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$-149 = -s_0 p_x + c_0 p_y \qquad s(\phi - \theta_0) = \frac{-149}{\rho}$$

$$\rho = \sqrt{p_x^2 + p_y^2}$$

$$p_x = \rho \cos\phi$$

$$p_y = \rho \sin\phi$$

$$\boxed{\theta_0 = \operatorname{atan2}(y, x) - \operatorname{atan2}\left(-149, \pm\sqrt{x^2 + y^2 - 149^2}\right)}$$

$$\phi = \operatorname{atan2}(p_y, p_x)$$

$$\rho\, c_0 s\phi - s_0 c\phi\, \rho = -149$$

$$\sin^2(\phi - \theta_0) + \cos^2(\phi - \theta_0) = 1$$

$$\cos(\phi - \theta_0) = \pm\sqrt{1 - \frac{149^2}{\rho^2}}$$

$$C_0 P_x + S_0 P_y = 432(C_1) + 432 C_1 C_2 - 432 S_1 S_2$$

$$-P_y = 432 S_1 + 432 C_1 S_2 + 432 C_2 S_1$$

$$k = (P_x C_0 + P_y S_0)^2 + P_z^2 - a_2^2 - a_3^2 - 432^2$$

$$n = 4 a_2^2 a_3^2 + 4 a_2^2 432^2$$

$$\boxed{\theta_2 = \operatorname{atan2}\left(k, \pm\sqrt{n - k^2}\right) - \operatorname{atan2}(a_3, 432)}$$

$$\left[T_3^0\right]^{-1} T_5^0 = T_5^3$$

$$\downarrow$$

$$\begin{bmatrix} C_4 C_5 & -C_4 S_5 & S_4 & 0 \\ C_5 S_4 & -S_4 S_5 & -C_4 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$f_1 = a_2 c_2 + a_3$

$f_2 = 4_{32} + a_2 s_2$

$\theta_{23} = \operatorname{atan2}\left(f_2(P_x c_0 + y s_0) - f_1 P_z,\ f_1(P_x c_0 + y s_0) + f_2 P_z\right)$

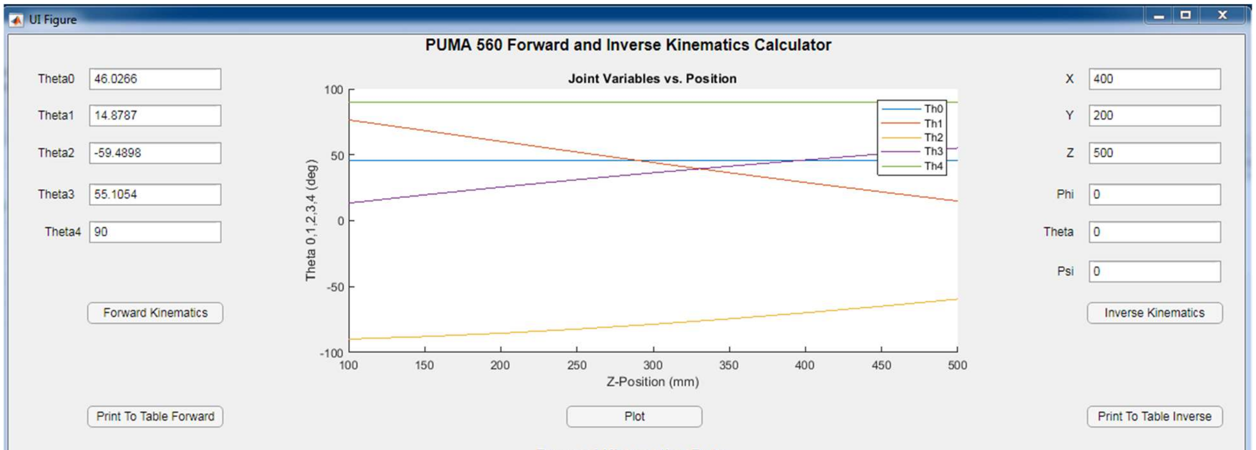
$$\boxed{\theta_1 = \theta_{23} - \theta_2}$$

For $\theta_4 > 0$

$$\boxed{\theta_3 = \operatorname{atan2}\left(c_0 s_{12} r_{13} - s_0 s_{12} r_{23} + c_{12} r_{33},\ c_0 c_{12} r_{13} + s_0 c_{12} r_{23} + s_{12} r_{33}\right)}$$

$$\boxed{\theta_4 = \operatorname{atan2}\left(\pm\sqrt{1 - (s_0 r_{13} - c_0 r_{23})^2},\ s_0 r_{13} - c_0 r_{23}\right)}$$

Results:



Forward Kinematics Data

	X	Y	Z	Phi	Theta	Psi
1	44.509	-166.2089	488.0412	0	72.6123	-161.7511
2	147.8122	-554.0182	258.1945	0	48.3589	-107.7637
3	-149	432	432	0	90	90
4	-305.4701	-149	305.4701	0	No Good	No Good
5	-42.094	-168.6238	679.5931	0	69.2952	-70.8934

Inverse Kinematics Data

	Theta0	Theta1	Theta2	Theta3	Theta4
1	46.0266	76.4786	-89.8199	13.3419	90
2	46.0266	68.3911	-87.9375	19.6181	90
3	46.0266	60.1901	-85.3945	25.5469	90
4	46.0266	52.0559	-82.2592	31.1235	90
5	46.0266	44.109	-78.5953	36.3752	90
6	46.0266	36.4138	-74.4559	41.3466	90
7	46.0266	28.9896	-69.8794	46.0898	90
8	46.0266	21.823	-64.8888	50.6583	90
9	46.0266	14.8787	-59.4898	55.1054	90

Matlab Code:

```
classdef Project_1_Test_New < matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)
        UIFigure                    matlab.ui.Figure
        ForwardKinematicsButton     matlab.ui.control.Button
        Theta0EditFieldLabel        matlab.ui.control.Label
        Theta0EditField             matlab.ui.control.EditField
        Theta1EditFieldLabel        matlab.ui.control.Label
        Theta1EditField             matlab.ui.control.EditField
        Theta2EditFieldLabel        matlab.ui.control.Label
        Theta2EditField             matlab.ui.control.EditField
        Theta3EditFieldLabel        matlab.ui.control.Label
        Theta3EditField             matlab.ui.control.EditField
        Theta4EditFieldLabel        matlab.ui.control.Label
        Theta4EditField             matlab.ui.control.EditField
        XEditFieldLabel             matlab.ui.control.Label
        XEditField                  matlab.ui.control.EditField
        YEditFieldLabel             matlab.ui.control.Label
        YEditField                  matlab.ui.control.EditField
        ZEditFieldLabel             matlab.ui.control.Label
        ZEditField                  matlab.ui.control.EditField
        PhiEditFieldLabel           matlab.ui.control.Label
        PhiEditField                matlab.ui.control.EditField
        ThetaEditFieldLabel         matlab.ui.control.Label
        ThetaEditField              matlab.ui.control.EditField
        PsiEditFieldLabel           matlab.ui.control.Label
        PsiEditField                matlab.ui.control.EditField
        UITableForward              matlab.ui.control.Table
        PrintToTableForwardButton   matlab.ui.control.Button
        InverseKinematicsButton     matlab.ui.control.Button
        PrintToTableInverseButton   matlab.ui.control.Button
        UITableInverse              matlab.ui.control.Table
        PUMA560ForwardandInverseKinematicsCalculatorLabel  matlab.ui.control.Label
        ForwardKinematicsDataLabel  matlab.ui.control.Label
        InverseKinematicsDataLabel  matlab.ui.control.Label
        Image                       matlab.ui.control.Image
    end



    % Callbacks that handle component events
    methods (Access = private)

        % Code that executes after component creation
        function startupFcn(app)

        end
```

% Button pushed function: ForwardKinematicsButton

```
function ForwardKinematicsButtonPushed(app, event)
%Code for calculating the forward kinematics

%Link Length
a1=0;
a2=432;
a3=432;
a4=0;
a5=0;

%Link Offset
d1=0;
d2=-149;
d3=0;
d4=0;
d5=0;

%Link Twist
al_1=-90;
al_2=0;
al_3=-90;
al_4=90;
al_5=0;

%Joint variables in degrees
c1=cosd(str2double(app.Theta0EditField.Value));
s1=sind(str2double(app.Theta0EditField.Value));
c2=cosd(str2double(app.Theta1EditField.Value));
s2=sind(str2double(app.Theta1EditField.Value));
c3=cosd(str2double(app.Theta2EditField.Value));
s3=sind(str2double(app.Theta2EditField.Value));
c4=cosd(str2double(app.Theta3EditField.Value));
s4=sind(str2double(app.Theta3EditField.Value));
c5=cosd(str2double(app.Theta4EditField.Value));
s5=sind(str2double(app.Theta4EditField.Value));

%Transformation Matrix
T_1_to_0 = [c1 -s1*cosd(al_1) s1*sind(al_1) a1*c1; s1 c1*cosd(al_1) -c1*sind(al_1) a1*s1; 0 sind(al_1) cosd(al_1) d1; 0 0 0 1];
T_2_to_1 = [c2 -s2*cosd(al_2) s2*sind(al_2) a2*c2; s2 c2*cosd(al_2) -c2*sind(al_2) a2*s2; 0 sind(al_2) cosd(al_2) d2; 0 0 0 1];
T_3_to_2 = [c3 -s3*cosd(al_3) s3*sind(al_3) a3*c3; s3 c3*cosd(al_3) -c3*sind(al_3) a3*s3; 0 sind(al_3) cosd(al_3) d3; 0 0 0 1];
T_4_to_3 = [c4 -s4*cosd(al_4) s4*sind(al_4) a4*c4; s4 c4*cosd(al_4) -c4*sind(al_4) a4*s4; 0 sind(al_4) cosd(al_4) d4; 0 0 0 1];
T_5_to_4 = [c5 -s5*cosd(al_5) s5*sind(al_5) a5*c5; s5 c5*cosd(al_5) -c5*sind(al_5) a5*s5; 0 sind(al_5) cosd(al_5) d5; 0 0 0 1];
T_5_to_0 = T_1_to_0 * T_2_to_1 * T_3_to_2 * T_4_to_3 * T_5_to_4;
```

```
%Position and Orientation
app.XEditField.Value=num2str(T_5_to_0(1,4));
app.YEditField.Value=num2str(T_5_to_0(2,4));
app.ZEditField.Value=num2str(T_5_to_0(3,4));

r33=T_5_to_0(3,3);
r31=T_5_to_0(3,1);
r32=T_5_to_0(3,2);

%Euler angles based on ZYZ transformation
theta_pos=atan2d(sqrt(1-r33.^2),r33);
psi_pos=atan2d(r32, -r31);
theta_neg=atan2d(-sqrt(1-r33.^2),r33);
psi_neg=atan2d(-r32, r31);

if ((abs(theta_pos) < 100) && (abs(psi_pos) < 266))
    app.ThetaEditField.Value = num2str(theta_pos);
    app.PsiEditField.Value = num2str(psi_pos);
elseif ((abs(theta_neg) < 100) && (abs(psi_neg) < 266))
    app.ThetaEditField.Value = num2str(theta_neg);
    app.PsiEditField.Value = num2str(psi_neg);
else
   app.ThetaEditField.Value = "No Good";
   app.PsiEditField.Value = "No Good";
end

app.PhiEditField.Value=num2str(0);
        end
```

% Button pushed function: PrintToTableForwardButton

```
        function PrintToTableForwardButtonPushed(app, event)
            %Table for Forward Kinematics
            if isempty(app.UITableForward.Data)
                    app.UITableForward.Data = {app.XEditField.Value, app.YEditField.Value, app.ZEditField.Value, 
app.PhiEditField.Value, app.ThetaEditField.Value, app.PsiEditField.Value};
            else
                    Data = get(app.UITableForward,'Data');
                    Data(end+1,:) = {app.XEditField.Value, app.YEditField.Value, app.ZEditField.Value, 
app.PhiEditField.Value, app.ThetaEditField.Value, app.PsiEditField.Value};
                    set(app.UITableForward,'Data',Data)
            end
        end
```

% Button pushed function: InverseKinematicsButton

```
        function InverseKinematicsButtonPushed(app, event)
%Code for calculating the inverse kinematics


%Link Lenth
a1=0;
a2=432;
a3=432;
a4=0;
a5=0;


%Link Offset
d1=0;
d2=-149;
d3=0;
d4=0;
d5=0;


%Positions and orientations
x = str2double(app.XEditField.Value);
y = str2double(app.YEditField.Value);
z = str2double(app.ZEditField.Value);
phi = str2double(app.PhiEditField.Value);
theta = str2double(app.ThetaEditField.Value);
psi = str2double(app.PsiEditField.Value);


r13=cosd(phi) * sind(theta);
r23=sind(phi) * sind(theta);
r33=cos(theta);




%Theta0_pos, Theta2_pos, Theta3_0p2p, Theta4_0p4p
theta0_pos = atan2d(y,x) - atan2d(-149, sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_pos) + (y*sind(theta0_pos)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_pos = atan2d(k,sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_pos) + a3;
f2 = 432 + a2*sind(theta2_pos);
theta23 = atan2d((f2*(x*cosd(theta0_pos) + (y*sind(theta0_pos))) - f1*z),f1*(x*cosd(theta0_pos) +
(y*sind(theta0_pos)))+f2*z);
theta1_0p2p = theta23 - theta2_pos;
theta3_0p2p = atan2d((-cosd(theta0_pos)*sind(theta1_0p2p + theta2_pos)*r13 - ...
    sind(theta0_pos)*sind(theta1_0p2p + theta2_pos)*r23 + cosd(theta1_0p2p + theta2_pos)*r33), ...
    (cosd(theta0_pos)*cosd(theta1_0p2p + theta2_pos)*r13 + sind(theta0_pos)*cosd(theta1_0p2p + theta2_pos) ...
    *r23 + sind(theta1_0p2p + theta2_pos)*r33));
theta4_0p4p = atan2d(sqrt(1 - (sind(theta0_pos)*r13 - cosd(theta0_pos)*r23).^2), ...
```

```
    sind(theta0_pos)*r13 - cosd(theta0_pos)*r23);



%Theta0_neg, Theta2_pos, Theta3_0n2p, Theta4_0n4p
theta0_neg = atan2d(y,x) - atan2d(-149, -1*sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_neg) + (y*sind(theta0_neg)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_pos = atan2d(k,sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_pos) + a3;
f2 = 432 + a2*sind(theta2_pos);
theta23 = atan2d((f2*(x*cosd(theta0_neg) + (y*sind(theta0_neg))) - f1*z),f1*(x*cosd(theta0_neg) +
(y*sind(theta0_neg)))+f2*z);
theta1_0n2p = theta23 - theta2_pos;
theta3_0n2p = atan2d((-cosd(theta0_neg)*sind(theta1_0n2p + theta2_pos)*r13 - ...
    sind(theta0_neg)*sind(theta1_0n2p + theta2_pos)*r23 + cosd(theta1_0n2p + theta2_pos)*r33), ...
    (cosd(theta0_neg)*cosd(theta1_0n2p + theta2_pos)*r13 + sind(theta0_neg)*cosd(theta1_0n2p + theta2_pos) ...
    *r23 + sind(theta1_0n2p + theta2_pos)*r33));
theta4_0n4p = atan2d(sqrt(1 - (sind(theta0_neg)*r13 - cosd(theta0_neg)*r23).^2), ...
    sind(theta0_neg)*r13 - cosd(theta0_neg)*r23);



%Theta0_pos, Theta2_neg, Theta3_0p2n, Theta4_0p4p
theta0_pos = atan2d(y,x) - atan2d(-149, sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_pos) + (y*sind(theta0_pos)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_neg = atan2d(k,-1*sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_neg) + a3;
f2 = 432 + a2*sind(theta2_neg);
theta23 = atan2d((f2*(x*cosd(theta0_pos) + (y*sind(theta0_pos))) - f1*z),f1*(x*cosd(theta0_pos) +
(y*sind(theta0_pos)))+f2*z);
theta1_0p2n = theta23 - theta2_neg;
theta3_0p2n = atan2d((-cosd(theta0_pos)*sind(theta1_0p2n + theta2_neg)*r13 - ...
    sind(theta0_pos)*sind(theta1_0p2n + theta2_neg)*r23 + cosd(theta1_0p2n + theta2_neg)*r33), ...
    (cosd(theta0_pos)*cosd(theta1_0p2n + theta2_neg)*r13 + sind(theta0_pos)*cosd(theta1_0p2n + theta2_neg) ...
    *r23 + sind(theta1_0p2n + theta2_neg)*r33));
theta4_0p4p = atan2d(sqrt(1 - (sind(theta0_pos)*r13 - cosd(theta0_pos)*r23).^2), ...
    sind(theta0_pos)*r13 - cosd(theta0_pos)*r23);



%Theta0_neg, Theta2_neg, Theta3_0n2n, Theta4_0n4p
theta0_neg = atan2d(y,x) - atan2d(-149, -1*sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_neg) + (y*sind(theta0_neg)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_neg = atan2d(k,-1*sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_neg) + a3;
f2 = 432 + a2*sind(theta2_neg);
theta23 = atan2d((f2*(x*cosd(theta0_neg) + (y*sind(theta0_neg))) - f1*z),f1*(x*cosd(theta0_neg) +
(y*sind(theta0_neg)))+f2*z);
theta1_0n2n = theta23 - theta2_neg;
```

```
theta3_0n2n = atan2d((-cosd(theta0_neg)*sind(theta1_0n2n + theta2_neg)*r13 - ...
    sind(theta0_neg)*sind(theta1_0n2n + theta2_neg)*r23 + cosd(theta1_0n2n + theta2_neg)*r33), ...
    (cosd(theta0_neg)*cosd(theta1_0n2n + theta2_neg)*r13 + sind(theta0_neg)*cosd(theta1_0n2n + theta2_neg) ...
    *r23 + sind(theta1_0n2n + theta2_neg)*r33));
theta4_0n4p = atan2d(sqrt(1 - (sind(theta0_neg)*r13 - cosd(theta0_neg)*r23).^2), ...
    sind(theta0_neg)*r13 - cosd(theta0_neg)*r23);




%Theta0_pos, Theta2_pos, Theta3_0p2p, Theta4_0p4n
theta0_pos = atan2d(y,x) - atan2d(-149,sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_pos) + (y*sind(theta0_pos)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_pos = atan2d(k,sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_pos) + a3;
f2 = 432 + a2*sind(theta2_pos);
theta23 = atan2d((f2*(x*cosd(theta0_pos) + (y*sind(theta0_pos))) - f1*z),f1*(x*cosd(theta0_pos) +
(y*sind(theta0_pos)))+f2*z);
theta1_0p2p = theta23 - theta2_pos;
theta4_0p4n = atan2d(-1*sqrt(1 - (sind(theta0_pos)*r13 - cosd(theta0_pos)*r23).^2), ...
    sind(theta0_pos)*r13 - cosd(theta0_pos)*r23);




%Theta0_neg, Theta2_pos, Theta3_0n2p, Theta4_0n4n
theta0_neg = atan2d(y,x) - atan2d(-149,-1*sqrt(x.^2 + y.^2 - 149^2));
k = (x*cosd(theta0_neg) + (y*sind(theta0_neg)))^2 + z.^2 - a2^2 - a3^2 - 432^2;
n = 4*(a2^2)*(a3^2) + 4*(a2^2)*(432^2);
theta2_pos = atan2d(k,sqrt(n - k.^2)) - atan2d(a3,432);
f1 = a2*cosd(theta2_pos) + a3;
f2 = 432 + a2*sind(theta2_pos);
theta23 = atan2d((f2*(x*cosd(theta0_neg) + (y*sind(theta0_neg))) - f1*z),f1*(x*cosd(theta0_neg) +
(y*sind(theta0_neg)))+f2*z);
theta1_0n2p = theta23 - theta2_pos;
theta4_0n4n = atan2d(-1*sqrt(1 - (sind(theta0_neg)*r13 - cosd(theta0_neg)*r23).^2), ...
    sind(theta0_neg)*r13 - cosd(theta0_neg)*r23);



        %Theta0 Out of Range Detection
        if (abs(theta0_pos) && abs(theta0_neg)) <= 160
            app.Theta0EditField.Value = num2str(theta0_pos);
        elseif abs(theta0_pos) > 160 && abs(theta0_neg) <= 160
            app.Theta0EditField.Value = num2str(theta0_neg);
        elseif abs(theta0_pos) <= 160 && abs(theta0_neg) > 160
            app.Theta0EditField.Value = num2str(theta0_pos);
        else
            app.Theta0EditField.Value = "Out of Range";
        end

        if (x^2 + y^2 - d3^2) < 0
            app.Theta0EditField.Value = "SINGULARITY";
        end
```

```matlab
  %Theta2 Out of Range Detection
if (abs(theta2_pos) && abs(theta2_neg)) <= 135
    app.Theta2EditField.Value = num2str(theta2_pos);
elseif abs(theta2_pos) > 135 && abs(theta2_neg) <= 135
    app.Theta2EditField.Value = num2str(theta2_neg);
elseif abs(theta2_pos) <= 135 && abs(theta2_neg) > 135
    app.Theta2EditField.Value = num2str(theta2_pos);
else
    app.Theta2EditField.Value = "Out of Range";
end

if (n - k^2) < 0
    app.Theta2EditField.Value = "SINGULARITY";
end

  %Theta1 Out of Range Detection
if (abs(theta1_0p2p) && abs(theta1_0n2p) && abs(theta1_0p2n) && abs(theta1_0n2n)) <= 125
    app.Theta1EditField.Value = num2str(theta1_0p2p);
elseif abs(theta1_0p2p) <= 125
    app.Theta1EditField.Value = num2str(theta1_0p2p);
elseif abs(theta1_0n2p) <= 125
    app.Theta1EditField.Value = num2str(theta1_0n2p);
elseif abs(theta1_0p2n) <= 125
    app.Theta1EditField.Value = num2str(theta1_0p2n);
elseif abs(theta1_0n2n) <= 125
    app.Theta1EditField.Value = num2str(theta1_0n2n);
else
    app.Theta1EditField.Value = "Out of Range";
end

  %Theta3 Out of Range Detection
if abs(theta3_0p2p) <= 100
    app.Theta3EditField.Value = num2str(theta3_0p2p);
elseif abs(theta3_0p2n) <= 100
    app.Theta3EditField.Value = num2str(theta3_0p2n);
elseif abs(theta3_0n2p) <= 100
    app.Theta3EditField.Value = num2str(theta3_0n2p);
elseif abs(theta3_0n2n) <= 100
    app.Theta3EditField.Value = num2str(theta3_0n2n);
else
    app.Theta3EditField.Value = "Out of Range";
end

%Theta4 Out of Range Detection
if abs(theta4_0n4p) <= 266
     app.Theta4EditField.Value = num2str(theta4_0n4p);
elseif abs(theta4_0p4p) <= 266
     app.Theta4EditField.Value = num2str(theta4_0p4p);
elseif abs(theta4_0p4n) <= 266
     app.Theta4EditField.Value = num2str(theta4_0p4n);
elseif abs(theta4_0n4n) <= 266
     app.Theta4EditField.Value = num2str(theta4_0n4n);
else
    app.Theta4EditField.Value = "Out of Range";
```

```
        end
      end


       % Button pushed function: PrintToTableInverseButton
      function PrintToTableInverseButtonPushed(app, event)
        %Table for Forward Kinematics

        if isempty(app.UITableInverse.Data)
              app.UITableInverse.Data = {app.Theta0EditField.Value, app.Theta1EditField.Value,
app.Theta2EditField.Value, app.Theta3EditField.Value, app.Theta4EditField.Value};
        else
              Data = get(app.UITableInverse,'Data');
              Data(end+1,:) = {app.Theta0EditField.Value, app.Theta1EditField.Value, app.Theta2EditField.Value,
app.Theta3EditField.Value, app.Theta4EditField.Value};
              set(app.UITableInverse,'Data',Data)
        end
      end


      % Button pushed function: PlotButton
      function PlotButtonPushed(app, event)
          %Position Change
        x = linspace(100,500,9);


          %Converting the table data from string to double
        Data = str2double(app.UITableInverse.Data);

        %Assigning all rows of each column to specific variables
        th0 = Data(:,1);
        th1 = Data(:,2);
        th2 = Data(:,3);
        th3 = Data(:,4);
        th4 = Data(:,5);


          %Plotting all of the joint variables
        plot(app.UIAxes, x, th0);
        drawnow;
        hold(app.UIAxes)
        plot(app.UIAxes, x, th1);
        plot(app.UIAxes, x, th2);
        plot(app.UIAxes, x, th3);
        plot(app.UIAxes, x, th4);

          %Plot legend
        legend(app.UIAxes, 'Th0','Th1','Th2','Th3','Th4')
      end
    end


    % Component initialization
    methods (Access = private)
```

```
% Create UIFigure and components
function createComponents(app)

    % Create UIFigure and hide until all components are created
    app.UIFigure = uifigure('Visible', 'off');
    app.UIFigure.Position = [100 100 1012 851];
    app.UIFigure.Name = 'UI Figure';

    % Create ForwardKinematicsButton
    app.ForwardKinematicsButton = uibutton(app.UIFigure, 'push');
    app.ForwardKinematicsButton.ButtonPushedFcn = createCallbackFcn(app,
@ForwardKinematicsButtonPushed, true);
    app.ForwardKinematicsButton.Position = [64 559 138 22];
    app.ForwardKinematicsButton.Text = 'Forward Kinematics';

    % Create Theta0EditFieldLabel
    app.Theta0EditFieldLabel = uilabel(app.UIFigure);
    app.Theta0EditFieldLabel.HorizontalAlignment = 'right';
    app.Theta0EditFieldLabel.Position = [25 796 43 22];
    app.Theta0EditFieldLabel.Text = 'Theta0';

    % Create Theta0EditField
    app.Theta0EditField = uieditfield(app.UIFigure, 'text');
    app.Theta0EditField.Position = [83 796 100 22];

    % Create Theta1EditFieldLabel
    app.Theta1EditFieldLabel = uilabel(app.UIFigure);
    app.Theta1EditFieldLabel.HorizontalAlignment = 'right';
    app.Theta1EditFieldLabel.Position = [25 759 43 22];
    app.Theta1EditFieldLabel.Text = 'Theta1';

    % Create Theta1EditField
    app.Theta1EditField = uieditfield(app.UIFigure, 'text');
    app.Theta1EditField.Position = [83 759 100 22];

    % Create Theta2EditFieldLabel
    app.Theta2EditFieldLabel = uilabel(app.UIFigure);
    app.Theta2EditFieldLabel.HorizontalAlignment = 'right';
    app.Theta2EditFieldLabel.Position = [25 721 43 22];
    app.Theta2EditFieldLabel.Text = 'Theta2';

    % Create Theta2EditField
    app.Theta2EditField = uieditfield(app.UIFigure, 'text');
    app.Theta2EditField.Position = [83 721 100 22];
```

```
% Create Theta3EditFieldLabel
app.Theta3EditFieldLabel = uilabel(app.UIFigure);
app.Theta3EditFieldLabel.HorizontalAlignment = 'right';
app.Theta3EditFieldLabel.Position = [25 679 43 22];
app.Theta3EditFieldLabel.Text = 'Theta3';


% Create Theta3EditField
app.Theta3EditField = uieditfield(app.UIFigure, 'text');
app.Theta3EditField.Position = [83 679 100 22];


% Create Theta4EditFieldLabel
app.Theta4EditFieldLabel = uilabel(app.UIFigure);
app.Theta4EditFieldLabel.HorizontalAlignment = 'right';
app.Theta4EditFieldLabel.Position = [32 641 43 22];
app.Theta4EditFieldLabel.Text = 'Theta4';


% Create Theta4EditField
app.Theta4EditField = uieditfield(app.UIFigure, 'text');
app.Theta4EditField.Position = [83 641 100 22];


% Create XEditFieldLabel
app.XEditFieldLabel = uilabel(app.UIFigure);
app.XEditFieldLabel.HorizontalAlignment = 'right';
app.XEditFieldLabel.Position = [849 796 25 22];
app.XEditFieldLabel.Text = 'X';


% Create XEditField
app.XEditField = uieditfield(app.UIFigure, 'text');
app.XEditField.Position = [889 796 100 22];


% Create YEditFieldLabel
app.YEditFieldLabel = uilabel(app.UIFigure);
app.YEditFieldLabel.HorizontalAlignment = 'right';
app.YEditFieldLabel.Position = [849 759 25 22];
app.YEditFieldLabel.Text = 'Y';


% Create YEditField
app.YEditField = uieditfield(app.UIFigure, 'text');
app.YEditField.Position = [889 759 100 22];


% Create ZEditFieldLabel
app.ZEditFieldLabel = uilabel(app.UIFigure);
app.ZEditFieldLabel.HorizontalAlignment = 'right';
app.ZEditFieldLabel.Position = [849 721 25 22];
app.ZEditFieldLabel.Text = 'Z';
```

```
        % Create ZEditField
        app.ZEditField = uieditfield(app.UIFigure, 'text');
        app.ZEditField.Position = [889 721 100 22];

        % Create PhiEditFieldLabel
        app.PhiEditFieldLabel = uilabel(app.UIFigure);
        app.PhiEditFieldLabel.HorizontalAlignment = 'right';
        app.PhiEditFieldLabel.Position = [849 679 25 22];
        app.PhiEditFieldLabel.Text = 'Phi';

        % Create PhiEditField
        app.PhiEditField = uieditfield(app.UIFigure, 'text');
        app.PhiEditField.Position = [889 679 100 22];

        % Create ThetaEditFieldLabel
        app.ThetaEditFieldLabel = uilabel(app.UIFigure);
        app.ThetaEditFieldLabel.HorizontalAlignment = 'right';
        app.ThetaEditFieldLabel.Position = [838 641 36 22];
        app.ThetaEditFieldLabel.Text = 'Theta';

        % Create ThetaEditField
        app.ThetaEditField = uieditfield(app.UIFigure, 'text');
        app.ThetaEditField.Position = [889 641 100 22];

        % Create PsiEditFieldLabel
        app.PsiEditFieldLabel = uilabel(app.UIFigure);
        app.PsiEditFieldLabel.HorizontalAlignment = 'right';
        app.PsiEditFieldLabel.Position = [849 601 25 22];
        app.PsiEditFieldLabel.Text = 'Psi';

        % Create PsiEditField
        app.PsiEditField = uieditfield(app.UIFigure, 'text');
        app.PsiEditField.Position = [889 601 100 22];

        % Create UITableForward
        app.UITableForward = uitable(app.UIFigure);
        app.UITableForward.ColumnName = {'X'; 'Y'; 'Z'; 'Phi'; 'Theta'; 'Psi'};
        app.UITableForward.RowName = {'1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'; '9'; '10'; '11'; '12'; '13'; '14'; '15'; '16'; '17'; '18';
'19'; '20'; ''};
        app.UITableForward.Interruptible = 'off';
        app.UITableForward.Position = [193 264 644 190];

        % Create PrintToTableForwardButton
        app.PrintToTableForwardButton = uibutton(app.UIFigure, 'push');
        app.PrintToTableForwardButton.ButtonPushedFcn = createCallbackFcn(app,
@PrintToTableForwardButtonPushed, true);
        app.PrintToTableForwardButton.Position = [64 503 138 22];
        app.PrintToTableForwardButton.Text = 'Print To Table Forward';
```

```
            % Create InverseKinematicsButton
            app.InverseKinematicsButton = uibutton(app.UIFigure, 'push');
            app.InverseKinematicsButton.ButtonPushedFcn = createCallbackFcn(app,
@InverseKinematicsButtonPushed, true);
            app.InverseKinematicsButton.Position = [870 559 138 22];
            app.InverseKinematicsButton.Text = 'Inverse Kinematics';


            % Create PrintToTableInverseButton
            app.PrintToTableInverseButton = uibutton(app.UIFigure, 'push');
            app.PrintToTableInverseButton.ButtonPushedFcn = createCallbackFcn(app,
@PrintToTableInverseButtonPushed, true);
            app.PrintToTableInverseButton.Position = [870 503 138 22];
            app.PrintToTableInverseButton.Text = 'Print To Table Inverse';


            % Create UITableInverse
            app.UITableInverse = uitable(app.UIFigure);
            app.UITableInverse.ColumnName = {'Theta0'; 'Theta1'; 'Theta2'; 'Theta3'; 'Theta4'};
            app.UITableInverse.RowName = {'1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'; '9'; '10'; '11'; '12'; '13'; '14'; '15'; '16'; '17'; '18';
'19'; '20'};
            app.UITableInverse.Interruptible = 'off';
            app.UITableInverse.Position = [193 20 644 193];


            % Create PUMA560ForwardandInverseKinematicsCalculatorLabel
            app.PUMA560ForwardandInverseKinematicsCalculatorLabel = uilabel(app.UIFigure);
            app.PUMA560ForwardandInverseKinematicsCalculatorLabel.FontSize = 16;
            app.PUMA560ForwardandInverseKinematicsCalculatorLabel.FontWeight = 'bold';
            app.PUMA560ForwardandInverseKinematicsCalculatorLabel.Position = [303 830 424 22];
            app.PUMA560ForwardandInverseKinematicsCalculatorLabel.Text = 'PUMA 560 Forward and Inverse
Kinematics Calculator';


            % Create ForwardKinematicsDataLabel
            app.ForwardKinematicsDataLabel = uilabel(app.UIFigure);
            app.ForwardKinematicsDataLabel.FontSize = 16;
            app.ForwardKinematicsDataLabel.FontWeight = 'bold';
            app.ForwardKinematicsDataLabel.Position = [415 462 199 22];
            app.ForwardKinematicsDataLabel.Text = 'Forward Kinematics Data';


            % Create InverseKinematicsDataLabel
            app.InverseKinematicsDataLabel = uilabel(app.UIFigure);
            app.InverseKinematicsDataLabel.FontSize = 16;
            app.InverseKinematicsDataLabel.FontWeight = 'bold';
            app.InverseKinematicsDataLabel.Position = [415 221 191 22];
            app.InverseKinematicsDataLabel.Text = 'Inverse Kinematics Data';


            % Create UIAxes
            app.UIAxes = uiaxes(app.UIFigure);
            title(app.UIAxes, 'Joint Variables vs. Position')
            xlabel(app.UIAxes, 'Z-Position (mm)')
```

```
            ylabel(app.UIAxes, 'Theta 0,1,2,3,4 (deg)')
            app.UIAxes.Position = [264 542 502 276];

            % Create PlotButton
            app.PlotButton = uibutton(app.UIFigure, 'push');
            app.PlotButton.ButtonPushedFcn = createCallbackFcn(app, @PlotButtonPushed, true);
            app.PlotButton.Position = [446 503 138 22];
            app.PlotButton.Text = 'Plot';

            % Show the figure after all components are created
            app.UIFigure.Visible = 'on';
        end
    end

    % App creation and deletion
    methods (Access = public)

        % Construct app
        function app = Project_1_Test_New_Latest

            % Create UIFigure and components
            createComponents(app)

            % Register the app with App Designer
            registerApp(app, app.UIFigure)

            % Execute the startup function
            runStartupFcn(app, @startupFcn)

            if nargout == 0
                clear app
            end
        end

        % Code that executes before app deletion
        function delete(app)

            % Delete UIFigure when app is deleted
            delete(app.UIFigure)
        end
    end
end
```